

Electromagnetic Metamaterials: Towards Higher Frequencies

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Abstract:

Over the past several years, artificially structured materials with unusual electromagnetic properties have generated an enormous amount of interest from the scientific and engineering communities. Much of this interest has been the result of the first demonstration, in 2000, of a “left-handed” composite material. The concept of a left-handed medium, for which both the electric permittivity and the magnetic permeability are simultaneously negative, was first put forward by Victor Veselago in 1968. However, Veselago’s conjecture was essentially ignored for thirty years due to the absence of naturally occurring materials or compounds that possess simultaneously negative permittivity and permeability.

The success of artificial materials—now frequently referred to as *metamaterials*—in the development of materials with left-handed electromagnetic properties illustrates the payoff associated with expanding our view as to what constitutes a material. Artificial materials can have unique properties that are rare or absent in known naturally occurring materials. For example, it has been known for decades that an array of conducting scattering elements can have a large effective dielectric constant; while this is a property common in naturally occurring insulators, such materials may have undesirable weight or other physical properties. The artificial dielectric structures have the same electromagnetic properties, but with the other physical properties improved. Existing applications of these artificial dielectrics include microwave lenses and antennas, which can be made much lighter than their counterparts made with conventional dielectrics. Another example of the use of artificial structures can be found in the recently demonstrated artificial magnetic metamaterials. Here, non-magnetic, conducting scattering elements are used to create a composite material having a tunable permeability. The artificial magnetic materials derive their effective magnetic properties via induction, and therefore sense only AC magnetic fields. This aspect has been utilized for the development of structures and devices that will focus or manipulate the RF fields in magnetic resonance imaging (MRI) systems. Such materials have a particular impact here, as they can be used without affecting or being affected by the large DC magnetic field distributions present. Many more exotic possibilities have recently been suggested. These new phenomena, such as “perfect lensing” or “optical antimatter” will require new and better metamaterials to be designed and fabricated.

The metamaterial designs so far introduced have consisted of arrays of conducting scattering elements, designed to have either predominantly magnetic or predominantly electric response to electromagnetic fields. Wires, either continuous or with periodic breaks, can provide a positive or a negative effective permittivity. Planar split ring resonators or wound coils (also known as

Swiss Rolls) can provide a positive or a negative effective permeability. For the case of magnetic metamaterials, the effective magnetism results as solenoidal currents are generated within the scattering elements, mimicking magnetic dipoles. Examples of the structures are shown in Fig. 1 below.



Fig. 1. Examples of metamaterial structures. The first two images are of “left-handed” metamaterials, while the third is of a “Swiss roll” used to form a magnetic metamaterial with desired properties at MHz frequencies.

The metamaterials illustrated in Fig. 1 were designed to operate at RF or microwave frequencies, as this frequency range was convenient for fabrication and measurements. As much of the initial metamaterials work centered around key proof-of-concept experiments, the frequency range where the phenomena of interest (such as negative refraction) were demonstrated was unimportant. However, given the availability of computation and of rapidly emerging meso- and nano-fabrication methods, reducing the physical scale of these initial metamaterials and thus raising the frequencies of operation is readily achievable. The development of artificial materials in certain wavelength regions may be particularly beneficial, as the range of material response is known to diminish in certain frequency bands. The scaling of a magnetic metamaterial structure to THz frequencies has recently been demonstrated, with the lattice dimension being on the order of ~ 0.030 mm, as opposed to the ~ 3 mm and larger cell sizes for the previously demonstrated metamaterials. Even higher frequency structures are expected to be reported soon.

The unusual electrodynamics of “left-handed” and similar metamaterials has prompted a flurry of activity in the analysis of new potential applications and devices—as well as new basic science. To implement these new concepts over the electromagnetic spectrum with the present conducting metamaterial designs will require advanced methods of fabrication. As we look to the future, an intriguing possible avenue of research will be the exploitation of the interplay between metamaterials and conventional materials. These hybrids can be expected to extend the available properties that either system alone possesses.

See these recent reviews:

D. R. Smith, J. B. Pendry, M. C. K. Wiltshire, “Metamaterials and negative refractive index,” *Science*, **305**, 288 (2004).

D. R. Smith, J. B. Pendry, “Reversing light with negative refraction,” *Physics Today*, 37 (June, 2004).